METROPOLITAN HIGHWAY SYSTEM
Stem to Stern Safety Review – Phase II
Executive Summary
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INTRODUCTION

The collapse of the I-90 tunnel ceiling in the Central Artery/Tunnel (CA/T) project on July 10, 2006 raised concerns about the inherent safety of the Metropolitan Highway System (MHS) and the newest structures to that system, the CA/T. In August of 2006, the Governor enacted emergency legislation under Executive Order No. 474 and established the independent MHS Safety Review Team and created a Special Safety Review Advisory Panel. The charge of the MHS Safety Review Team was to conduct an independent 'Stem to Stern' audit of the MHS infrastructure to provide an assessment of its near and long-term safety. As such, the engineering firm Wiss, Janney, Elstner Associates, Inc. (WJE) was retained to conduct the engineering study and consultation of the principal elements of the MHS while life-safety systems were investigated by subconsultants to WJE: Schirmer Engineering, and Environmental Systems Design (ESD).

The Safety Review as intentioned by the Executive Order was comprised of the following phases:
Phase I: August 2006 – December 2006
Phase IA: January 2007 – June 2007
Phase II: July 2007 – June 2008

ORGANIZATION

Phase II was organized in similar fashion as that for the earlier phases of the safety review.

I. Safety Review Team chaired by the Director, was comprised of:
   a. Executive Office of Transportation
   b. Wiss, Janney, Elstner Associates, Inc.; Lead engineering consultant
   c. Schirmer Engineering Corp.; Life Safety Systems experts
   d. Environmental Systems Design (ESD); electrical/mechanical experts

II. Special Advisory Panel consisted of the following members:
   a. Robert E. Skinner, Jr., PE (Chairman)
      Executive Director, Transportation Research Board
   b. Francis J. Lombardi, PE
      Chief Engineer, Port Authority of NY/NJ
   c. Robert B. Pond, PE, PhD
      Chair, Engineering Science Department, Loyola College
   d. Andrew Whittle, PE, PhD
      Professor of Civil and Environmental Engineering, Massachusetts Institute of Technology

III. Implementation Team chaired by the Director, comprised of:
   a. Executive Office of Transportation
   b. Massachusetts Turnpike Authority
   c. Massachusetts Highway Department
   d. Wiss, Janney, Elstner Associates, Inc and subconsultants

IV. Federal Oversight provided by:
   a. Federal Highway Administration
   b. Department of Transportation, Office of the Inspector General
   c. U.S. Army Corps of Engineers (technical consultants to the DOT-IG)

APPROACH AND METHODOLOGY

Initial planning activities were conducted based on a review of outstanding issues from previous phases and the expanded physical scope. Review of the relevant record drawings and field reconnaissance was conducted, in order that a general understanding be developed to determine the nature and extent of the structural or life safety systems, design intent, physical conditions and access limitations, and logistics/staffing needed to meet the project objectives.

As a result, a Phase II scope was developed focusing on four areas:

1. *Phase I follow-up*. Follow-up of issues that were identified in Phase I however required more in-depth review and investigation to determine the impact on the safety of the CA/T.
2. *Special Studies*. These areas included those findings from Phase I which were more complex and potentially impacting the long-term safety of the CA/T. Scope of work included; modeling of fire resistance of the ceiling plenums, incomplete tendon grouting of concrete viaducts, premature cracking of concrete roadway overlays, and further investigation into tunnel and building leaks.
3. *Metropolitan Highway System beyond the CA/T*. This included inspections and investigation into structures such as the Sumner, Callahan, and CANA Tunnels and the overpasses, toll booths structures, and Prudential tunnels, as well as other structures owned either by private developments or other state and local agencies.
4. *Consulting on Implementation of Recommendations.* In the mitigation of identified safety deficiencies, design and installation procedures were recommended and those submitted by the structure owners were reviewed. Follow-up verification of reported corrective actions was conducted to ensure adequacy of the repair.

Areas of interest were defined in one of two categories; (1) Structural or (2) Life Safety Systems Life safety systems consist of several detection, response, and protection systems and features, operating alone or as part of a system. Examples include: fire resistive construction, fire detection systems, communication systems, traffic control systems, fire suppression systems (standpipes and portable fire extinguishers), ventilation system, emergency response plans and control of hazardous material, emergency egress features, operations and control system, and power systems.

As the lead engineering consultant conducting the review, WJE (and its sub-consultants; Schirmer Engineering and ESD) conducted hands-on inspections, design reviews, engineering calculations, and lab testing and analyses for both the structural and life safety aspects of the MHS. Safety concerns (or simply conditions of interest) arose were recorded as *reportable*

conditions. Throughout the process, the baseline condition and level of urgency was determined for each reportable condition as follows:

- **IC**: Immediate or dangerous condition (immediately reported to the MTA)
- **R1**: Remediation recommended as soon as possible
- **R2**: Remediation recommended in coordination with near-term maintenance and capital improvement programs
- **MR**: Monitoring recommended; consider remediation if condition worsens
- **NA**: No follow-up under stem to stern safety review
- **CR**: Phase II follow-up work resolved concern
- **MI**: Item that requires regular maintenance and/or remediation

Additionally, key structural and life safety elements were identified and assigned a priority rating based on the *relative* likelihood of failure in the near term, and the consequences of failure. Priorities were generally assigned as follows:

Priority 1

- Structural- elements whose failure in the near term is more likely than that of common or typical elements, and whose failure would have a high probability of rendering the affected structure hazardous to users or employees in the general vicinity.
- Life Safety- elements which are deficient in capability relative to the design basis or current standard performance objectives and therefore represent a significant risk to the life and limb of the public, employees, and responding emergency personnel.

Priority 2

- Structural- structures whose failure is relatively unlikely in the near term or whose failure is not likely to be immediately hazardous.
- Life Safety- elements with some level of redundancy and appreciable factor of safety, including systems and features which are not in full compliance with specific standards or recommend practices but have the capability to achieve performance objectives established as the basis of design.

Timing

Field work related to the Phase II scope was carried out in two primary campaigns: (1) Follow-up investigations of CA/T facilities and initial investigations of structures along the Boston Extension (Sept-Oct 2007) (2) Railroad structures along the Boston Extension and inspections to verify the status of repairs and retrofit pursuant to Phase I recommendations (March 2008).

Review was conducted by both the Federal Highway Administration (FHWA) and the U.S. Department of Transportation's Office of the Inspector General (DOT-IG), and input was received real-time, through detailed discussion at monthly Safety Review Team meetings and teleconferencing sessions. Meeting separately and providing on-going advice on methodology or engineering significance, the Special Advisory Panel played an important role in the safety review through their observations and advice to ensure a thorough, objective, and effective process.

FINDINGS AND RECOMMENDATIONS

A detailed description of the review process and the findings and recommendations are fully documented in 24 volumes, to include a Summary and Overview report (Volume 1). Drafted by WJE, the reports were then reviewed by the FHWA and DOT-IG who made written comments on the reports, which were either incorporated into the report or responded to in writing as to a rationale for non-concurrence. Therefore, not all conclusions or recommendations presented in

the Phase II reports are necessarily in full agreement by either or both of these two federal agencies, however any differences will be appended to the final report.

Structural and life safety systems of the Central Artery/Tunnel were designed using appropriate modern standards. In general, these systems are robust and, where appropriate, redundancy is provided. The designs of the older elements of the MHS appear to be consistent with the standards of the period, although detailed design criteria were not available. The level of distress and deterioration in these older structures is consistent with their age and exposure.

Nonetheless, several structural deficiencies and concerns exist that could affect near-term or long-term safety. Some of these conditions were uncovered by the stem to stern review; others were at least partially known in advance of this study and were subsequently investigated under this review. The following sections describe the most notable deficiencies and concerns.

Structural Capacity

Tunnel Ceiling Supports

With respect to the ceiling support systems, no noteworthy structural deficiencies were identified at the I-93 Central Artery Tunnel or the CANA Tunnel. Following the collapse in the I-90 connector, the ceiling system was analyzed and retrofitted using undercut mechanical anchors, resolving the safety concern. The Phase II investigation of ceiling systems focused on adhesive anchors in the Ted Williams, Sumner and Callahan tunnels. If there is a commonality among the performance of adhesive anchors in the Ted Williams, Sumner, and Callahan tunnels, it is the high degree of variability and unpredictability. This variability undermines confidence in long-term performance of adhesive anchors.

Ted Williams Tunnel Anchors. Most of the TWT epoxy anchors have not exhibited indications of susceptibility of creep under sustained loads. Nevertheless, the long-term creep performance of the existing anchors remains in question. A more extensive and rigorous program of creep testing of the existing epoxy anchors is recommended. Fortunately, the ceiling systems are capable of redistributing loads in the event of individual anchor failures however diligent inspections and as-needed retrofits will assure safety in the short term until long-term recommendations are implemented.

The structural design of the direct-attached ceilings, located in the portal regions and other localized areas of the TWT, renders the epoxy anchors effectively inaccessible for visual inspection. In absence of a practical, cost-effective means to inspect and monitor these epoxy anchors, it is recommended that the direct-attached ceilings be retrofitted by adding either external supplemental stringers or by their removal.

A special study of the fire resistance of the TWT anchors was based on heat exposures of 20 and 30 megawatt fires quantified for worst-case conditions using model simulations. Results lead to a recommendation to review and revise the emergency response procedures or conduct selected retrofits of the ceiling system as appropriate.

Sumner Tunnel Anchors. Tests of anchors in suspect concrete under low loads were successful, however the failure rate was considered exceedingly high. Accordingly, it is recommended that all adhesive anchors supporting the existing ceiling system be replaced as part of a long-term liner repair program. In the meantime, comprehensive systematic and regular inspection of the liner, anchors, and ceiling components is recommended at an interval not to exceed six months.

Callahan Tunnel Anchors. The anchors in the Callahan tunnel frequently exhibit gaps between the yoke and concrete liner. It is believed that a majority are believed to be due to creep-related deformation and slippage of the epoxy adhesive. Although the Callahan anchors performed well in recent short term proof tests, the observed behavior indicates a long-term deficiency to be addressed. As such, the recommendation is a complete replacement of the anchorage system in the Callahan tunnel with inspections occurring at no more than six month intervals until replacement.

Prudential Tunnel- Suspended Ceiling Slab. At the Hynes Convention Center in the Prudential Tunnel, a structural analysis showed that the system is sufficiently redundant to preclude progressive collapse in the event of failure of any one hanger. In late 2007, the owners of the Hynes Convention Center engaged an engineering firm to investigate the suspended tunnel slab who recommended both near-term and long-term repairs. The S2S concurs with these recommendations.

Leverett Pier Cap

Phase II studies identified a structural deficiency of a pier supporting the Leverett Bridge. Detailed structural analyses revealed that the nominal capacity was less than required by the design specifications (1992 AASHTO Standard Specifications for Highway Bridges). However, these analyses also showed that the structure was safe for normal traffic, including permit vehicles with gross weights of up to 99 kips.

Strengthening is recommended to assure long-term structural integrity. Also, sealing of the cold joint along the top of the cap beam is recommended to prevent further moisture intrusion into the crack. Until the crack is reinforced, changes in crack width are being monitored by continuous electronic monitors.

Sumner, Callahan, and CANA Tunnels

Other than the concerns regarding ceiling anchorage is previously described, no structural capacity concerns at the Callahan and CANA tunnels were identified. Despite the advanced deterioration of the Sumner tunnel liner, the circular steel and concrete liners, acting alone or together, were found to have adequate strength to safely resist the expected earth pressures and hydrostatic forces. Limited non-destructive testing of the steel liner did not uncover any indication of corrosion. The concrete is chloride contaminated but otherwise in fair condition. Repairs to the concrete liner are recommended in conjunction with the ceiling hanger retrofits previously discussed.

Boston Extension and the Prudential Tunnel

The structural systems employed in the buildings and bridges spanning the Boston Extension are straightforward, but not as robust as the CA/T structures. Furthermore, the 40-year-old structures are suffering the expected effects of exposure to the harsh northern climate. In particular, exposure to deicing salts has resulted in chloride-induced corrosion of embedded reinforcing and

section loss of steel members in some areas. The most noteworthy examples of structural capacity concerns are described in the following paragraphs.

Private Building. The building structure exhibits signs of severe deterioration and distress. This structural system has not performed well in the harsh environment. Particular concerns were noted pertaining to a cracks, spalling, and poor embedment on various structural components. At the time of this writing, repairs were well advanced .

At the time of these discoveries, immediate actions were undertaken by the owner to rectify the issues in the short term, and subsequent follow-up with contract work should resolve any concerns raised. In view of the advanced state of the structural concerns, the Safety Review Team recommends that an inspection program be established to provide a formal process to monitor structural conditions and the performance of the various repairs conducted on structures spanning the roadway.

Prudential tunnel deterioration of cantilevered cap beams. Within the Prudential Tunnel, various concrete beams were severely deteriorated. Although not judged to pose an immediate safety threat, an engineered repair was recommended for installation as soon as possible.

Immediate Safety Hazards, in General

The Phase II safety review uncovered several conditions related to structural systems that were judged to be unsafe and warranted immediate follow-up action. These conditions did not relate to integrity of primary structural systems; rather, most immediate safety concerns related to loose or unsound concrete over traffic, or fractured or damaged metal poles.

Loose or Unsound Concrete over Traffic. Most frequently, loose concrete occurred along the exterior stringers and overpasses, where corrosion at the flange edge caused delamination and spalling along the edge of the concrete deck. Damage was also observed where moisture and salts had penetrated through the bridge deck.

Additionally, concrete pier caps were frequently spalled or delaminated due to corrosion of embedded reinforcement. The spalled and deteriorated concrete conditions have developed over many years, and represent a deterioration mechanism that is common to the transportation infrastructure. Nonetheless, the relatively high frequency of such conditions occurring along the Boston Extension suggest that more intensive inspection and maintenance is needed to mitigate the hazard.

Damaged Metal Poles. Metal poles along the Boston Extension and CA/T were inspected and in addition to structural deficiencies related to impact damage and original construction deficiencies, advanced corrosion of some of the older poles was observed. Structural deficiencies in metal poles, especially damage due to vehicular impact, will be an ongoing problem. Of the 3,500 metal masts or poles located in the CA/T, 54 required repair or retrofit. In half of those cases, the construction deficiency was considered dangerous, requiring an immediate repair. Future damage can be expected from corrosion and vehicular impact. As such, the Safety Review Team recommends that all metal poles be included as part of the regular inspection and maintenance program.

Long-term Threats to Structural Safety

Central Artery/Tunnel

Deterioration due to tunnel and building leaks. Special studies of leakage into tunnels and buildings indicated a variety of leakage sources with seasonal variation. But on the average, the leakage rate is consistent with the most stringent requirements for tunnel leakage found by this study. Most of the water leaking into the tunnels and buildings is high in chlorides, which exacerbate corrosion of embedded reinforcement and exposed steel. As such, leaks threaten long-term structural integrity of the tunnels if the protection systems are not maintained.

Pattern cracking of tunnel roof structures and pier columns. Field observations and petrographic examination of core samples indicated that the concrete distress is consistent with early age cracks that occurred when the concrete was still plastic. Alkali silica reaction (ASR) or other serious detrimental material problems were not identified in the areas studied; although the limited sampling does not rule out the risk of ASR at other project locations. Treatment of the cracks to prevent water ingress is recommended.

Premature deterioration of concrete overlays. Investigation revealed that the roadway overlay distress most frequently occurs along transverse construction joints, which were intended to align with construction joints in the structural slab. Many of the sawn joints did not align with the underlying construction joint, and the overlay failed because it could not accommodate the seasonal movement at the construction joint. Some joints are vulnerable to cracking and delamination because bond stresses are increased at the discontinuity. The performance of the overlays on the elevated structures was generally very good. As the overlay is the primary line of defense against moisture and chloride ingress at joints in precast segments, inspection and maintenance of the overlay in these areas is critical to long-term safety.

Incomplete tendon grouting. Post-tensioned tendon reinforcement consisting of either multi-wire strands or threaded bars were used in many concrete viaducts. The grout's purpose is to provide bond between the tendon and the surrounding concrete and to protect the steel tendon from potentially damaging conditions. WJE's investigation revealed that there is sufficient capacity to resist service loads even with partial loss of post-tensioning forces as a result of strand deterioration should that occur. However the installation of acoustic-monitoring systems at several of the more critical post-tensioned structure should be considered. These systems would serve as an early warning of strand deterioration.

Sumner and Callahan Tunnels

The Sumner and Callahan tunnels show deterioration due to chloride-induced corrosion. The quality of the shotcrete liner is fair to poor, and future deterioration can be expected where moisture and salts penetrate the concrete. Future repairs to the Sumner and Callahan tunnels' liner and roadway structure will eventually be needed.

The CANA Tunnel did not exhibit any unusual indications of premature deterioration that threaten long-term structural integrity.

Boston Extension and Prudential Tunnel

Moisture and deicing salts are the primary threats to long-term structural integrity of members. As the structures along the Boston extension are not as conservatively designed as those in the CA/T, they are more vulnerable to loss of structural integrity due to exposure.

Life Safety Systems

Central Artery/Tunnel

The review found that the design of the life safety elements are consistent with the basis of design and the provisions of NFPA 502 *Standard for Road Tunnels, Bridges, and other Limited Access Highways*, 2004 edition. However, the review revealed conditions that should be addressed by ownership in the near term, as described below.

Automatic Fire Detection and Detection Time. Notably, the components of the system are still in the installation phase. As such, high priority should be given to their immediate completion of the system procured by the MTA. If the plan is implemented successfully, the result will be substantially better than originally anticipated.

Integrated Project Control System. This system completion is in progress and the full integration of all life safety systems, should be given high priority in the near term.

Maintenance Programs. The primary elements of the maintenance program are maintenance schedules, procedures, and actions. Based on the harsh environment the highway elements are exposed to, there is a continual need to upgrade maintenance programs for critical systems.

Emergency Response and Training Programs. Inter-agency training must continue to be performed and updated to reflect "lessons learned". The training program should include variations of incidents, third party observers, and post exercise briefings and reports to refine future efforts. Specific emergency response and trainings plans should include specific modules on large scale fire events and the potential localized failure of the suspended ceiling systems.

Routine Reviews. Life safety protection for tunnels continues to evolve. As new considerations are made known through the nationally recognized standards, the highway system should be reviewed against these new considerations to evaluate how the existing facilities compare and to identify future modifications that should be incorporated to maintain a high level of life safety.

Sumner and Callahan Tunnels

The Sumner and Callahan life safety systems were evaluated and associated deficiencies should be addressed by the MTA. As points of egress for the Sumner and Callahan Tunnels are the portals, it puts more dependency on other systems. While the current systems are sufficient to address design effects, the lack of robustness suggests the review of the life safety systems for developing redundancies.

CANA Tunnel

The CANA Tunnel and ventilation building life safety systems have few areas where the life safety systems do not fully comply with NFPA 502, and has the least concerns of the tunnels reviewed.

Prudential Tunnel

The Prudential Tunnel was a result of separate projects for several buildings constructed over the course of many years from the mid 1960s to the early 1980s, and does not have all of the required elements for today's life safety systems. It is understood that with further air rights development, the MTA will require the next agreement to include an upgrade to the tunnel life safety systems.

Implementation of Stem to Stern Recommendations

The "implementation plan" is a term used to describe the entire list of identified reportable conditions, the proposed plan of action to address the condition, and schedule when known.

Independent Verification. Throughout Phase II, the stem to stern team performed site visits and document reviews to verify that various reportable conditions have been addressed. The purpose was not to serve as the quality control or quality assurance of the repair, but was to perform an independent verification that remediation measures have been implemented with feedback from, representatives of the Safety Review Team.

For the structural reportable conditions, implementation verification commonly included a field visit to observe the remediation measure. The implementation verification field visits were performed in conjunction with the Phase II field work in October 2007 and March 2008. In addition, implementation verification site visits were also performed during June 2008. For life safety reportable conditions the verification often included review of available documentation, discussions with the MTA and CA/T personnel, and an occasional field visit when required. Because many of the life safety reportable conditions directly relate to potential maintenance issues in the future, verification efforts also included a review of the preventative maintenance program to ensure that procedures are in place to address similar conditions in the future. Individual reports were created for each verification inspection or item resolution, and these reports discuss the steps taken to address the concern and the status of the reportable condition after the independent verification.

Summary of Implementation Status. Throughout the course of Phase II, implementation verifications were performed by the stem to stern team. All immediate concern (IC) conditions identified in Phase I have been closed or reclassified based on the verification inspections. These include such items as removal of loose concrete that presents an overhead hazard, removal of debris from the tunnel exhaust plenums, repair of standpipe sections as well as removal or replacement of loose, damaged, corroded, or improperly anchored signs and luminaires. A summary of the current status of the conditions identified in Phase I is shown below.

Summary of Reportable Condition Implementation Status by Phase

Reportable Condition	Total Identified		Remain Open	
	I	II	I	II
IC: Immediate or dangerous condition	35	66	0	1*
R1: Repair recommended as soon as possible	80	59	27	47
R2: Repair with maintenance/capital programs	64	74	27	42
Totals:	378		143	

CONCLUSION

The completion of Phase II signifies the conclusion of the "Stem to Stern" Safety Review as defined by Executive Order No. 474. In general, the CA/T was conservatively designed, fundamentally robust, with built-in redundancy. The MHS infrastructure outside the CA/T is demonstrating the signs of deterioration from exposure to a harsh environment. As such, more frequent on-site inspections will allow for the identification of issues that can develop in a relatively short period of time (a few months) and result in a safety concern to the public.

While hundreds of conditions have been documented and many of those remediated, thus eliminating the safety hazard, there are many more projects awaiting resources to eliminate the condition and close the item out. Some items, such as the leakage cessation, will continue far into the future at some maintenance level, as leaks that are sealed may reoccur, or leaks can develop in completely new locations. In these cases, it is the management plan that will define the methodology and prioritization to effectively and efficiently address the issue before it creates secondary damage or presents a larger safety concern.

Despite the thousands of hours by dedicated engineers going over every accessible foot of the structures on the MHS, in many ways, documenting a flawed detail may be accurately described as the easier part. Finding a solution, designing it in light of the complex interconnected systems that exist in the CA/T, and making the repair while the CA/T continues to be an operational facility, will take significant resources with dedicated staff to see the repairs through to completion. The establishment of the CA/T Repair and Maintenance Trust Fund in January 2008, will assist in providing some of the needed resources. Its purpose is to provide monies toward repairs on the CA/T which were not due to wear and tear, but rather a flaw in the design or construction of the facility.

As detailed in the reports, the CA/T is a uniquely complex structure with many inter-related systems to protect the structures and the life safety systems of the facility. Future repairs will require an understanding of these inter-relationships to ensure that one repair doesn't beget a different problem. In such instances, it may be helpful to retain other consultant engineers with expertise in the particular area of remediation, in order to conduct a peer review. For the more complex repairs, this practice would add further confidence that the repair methodology is sound and will provide the best possible results.

Given the importance of this vital transportation facility, the focus going forward should be on rigorous inspections and maintenance of protection systems and other elements with limited service life, such that the primary structural systems last indefinitely.